The X(3872) at the Tevatron

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Representing the

CDF II & DØ

Collaborations

— PANIC05 —

A Little $X(3872)$ Background:

- Aug'03: Belle Annouced Discovery of $X(3872) \to J/\psi\pi^+\pi^-$
- Obvious Interpretation: $^3D_2$ Charmonium?... But X Too Heavy
- Curious Facts: #1: $M(X) \approx M(D^0\overline{D}^{*0})$

  #2: Favors High $\pi\pi$-Masses $\to J/\psi\rho$ Decay?

  ... $J/\psi\rho \to$ Isospin Breaking If $c\bar{c}$

- Seductive Hypothesis: Deuteron-Like D^0-$\overline{D}^{*0}$ "Molecule"?

  > Naturally Explains: Mass & Isospin

- Other Hypotheses: cq-$\bar{c}\bar{q}$-Diquarks, $c\bar{c}g$-Hybrid, Cusp
- Spring'05: Belle Measuring Angular Distributions & $M(\pi\pi)$:

  $\Longrightarrow$ Argues 1^{++} Preferred [hep-ex/0505038]

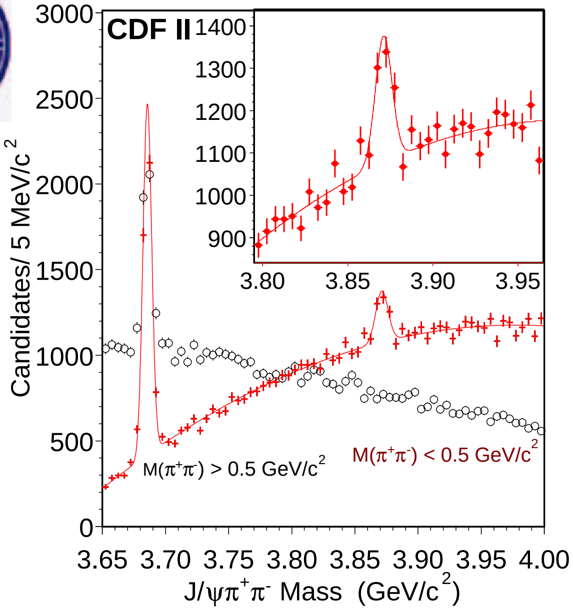
- Range of Strong Opinions, But...

⇒ No Interpretation Firmly Established ⇐

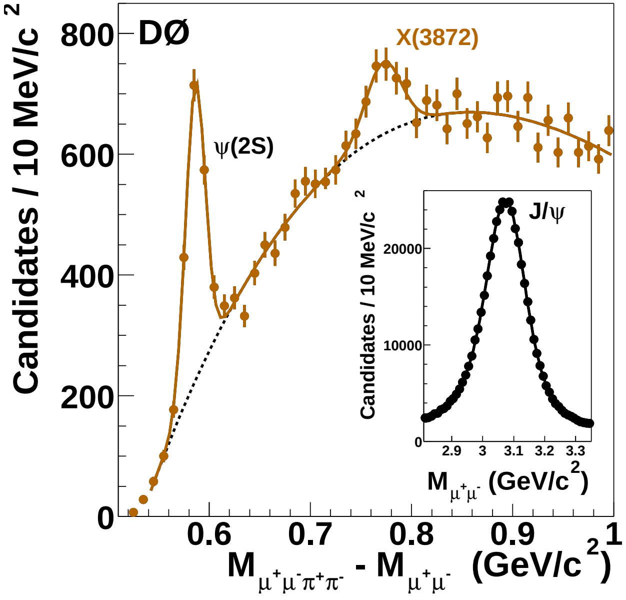
$X(3872) \to J/\psi\pi^+\pi^-$ in $\bar{p}p$ @ $\sqrt{s} = 1.96$ TeV

- $X(3872)$ Quickly Confirmed:

PRL 93, 072001 (2004)



PRL 93, 162002 (2004)

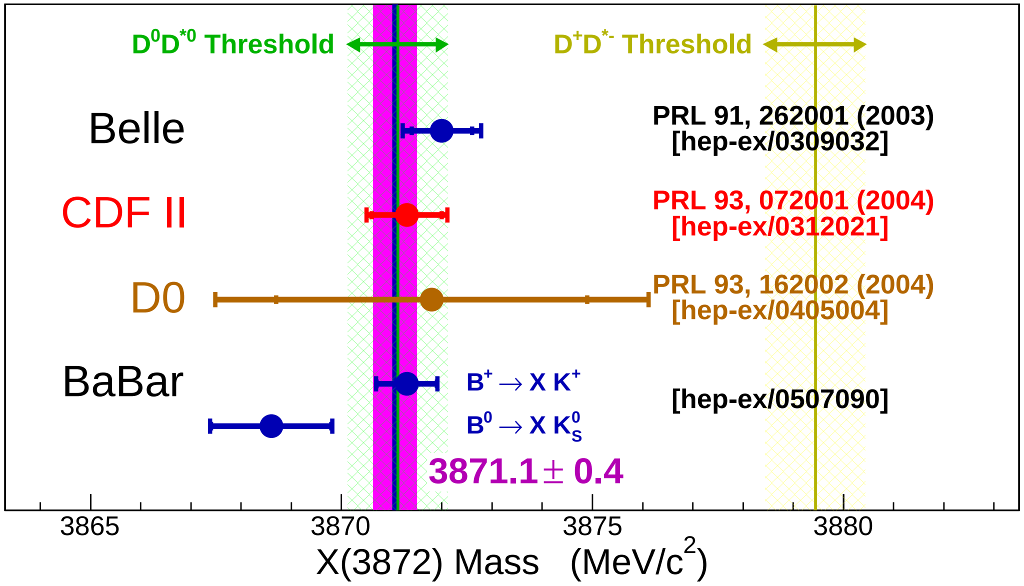


- Mass Measurements:

—$X(3872)$ Dead-On

D^0D^{*0} Threshold

$\Rightarrow$ Is X $D^0\overline{D}^{*0}$ Molecule?



Properties: $X(3872)$ Versus $\psi(2S)$

- : Fraction of Yield for Various Properties:

a) $p_T(J/\psi\pi\pi) > 15\,GeV$

b) $|y| < 1$

c) $\cos(\theta_\pi) < 0.4$ [π Helicity]

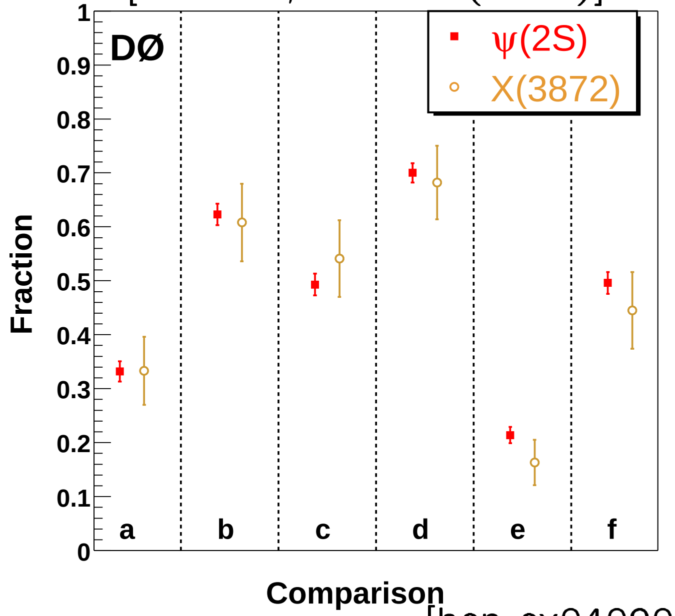
d) Proper Decay Length $< 100\,\mu$m

e) $\dfrac{p(X)}{p(X) + \sum_{\Delta R<0.5} p(Tracks)} = 1$

f) $\cos(\theta_\mu) < 0.4$ [μ Helicity]

$\Rightarrow$ $X(3872)$ & $\psi(2S)$ Production Appear Indistinguishable

[PRL 93, 162002 (2004)]



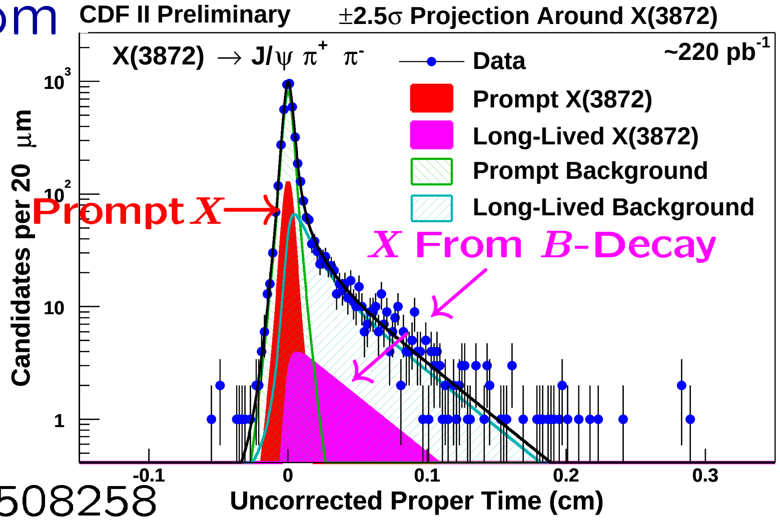
- : Proper Decay Length: Measure Fraction of X's From B-Decay Vs. Prompt

$\rightarrow$ $28.3 \pm 1.0 \pm 0.7\%$ $\psi(2S)$ From B's

$\rightarrow$ $16.1 \pm 4.9 \pm 2.0\%$ X's From B's

$\Longrightarrow$ X Production Looks Rather Charmonium-Like!

[hep-ex0409052]



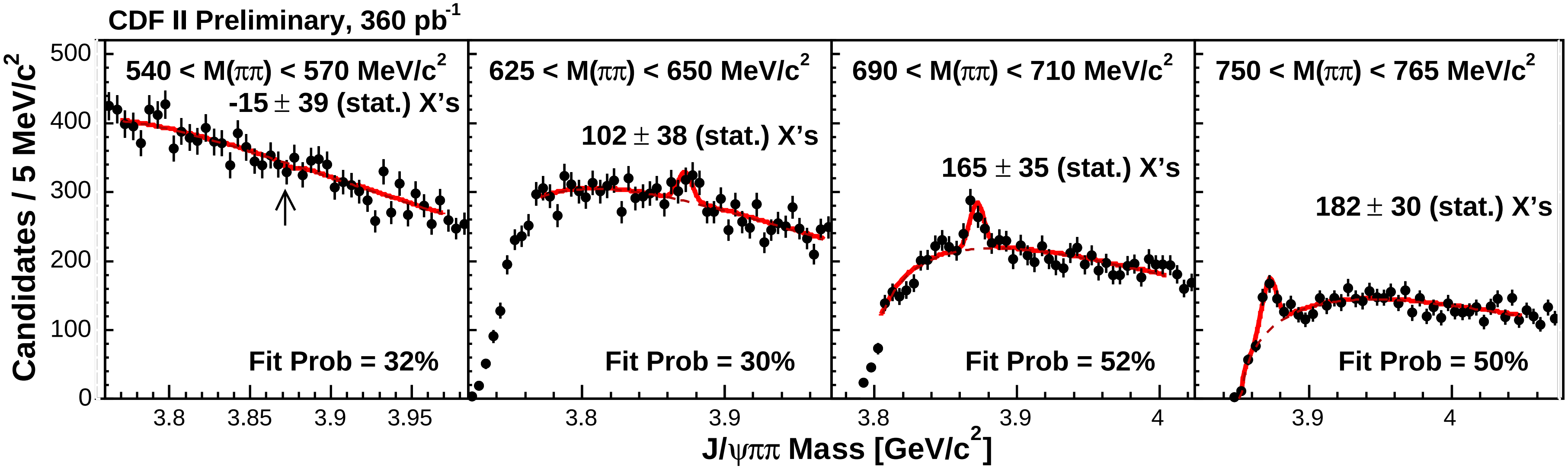
e.g. See:
hep-ex/0505083, hep-ph/0506222, hep-ph/0508258

Dipion Mass Spectrum:

- Belle Discovery: High $\pi\pi$ Masses Favored
  $\Rightarrow$ Contrary to Some $c\bar{c}$ Options
- Speculation: Actually $X \to J/\psi\rho$? $\Leftarrow$ Isospin Violating for $c\bar{c}$!
  $\Rightarrow$ Another Hint of Molecular Nature??

- CDF has Large X Sample — But Large Background Too
  1) Divide $J/\psi\pi\pi$ Sample Into "Slices" of $M(\pi\pi)$
  2) Fit Each Slice for $\psi(2S)$ and $X(3872)$ Yields

For Example (360 pb$^{-1} \to 1.3$k X's):



3) Correct for Efficiency $\Longrightarrow$ Dipion Mass Spectrum

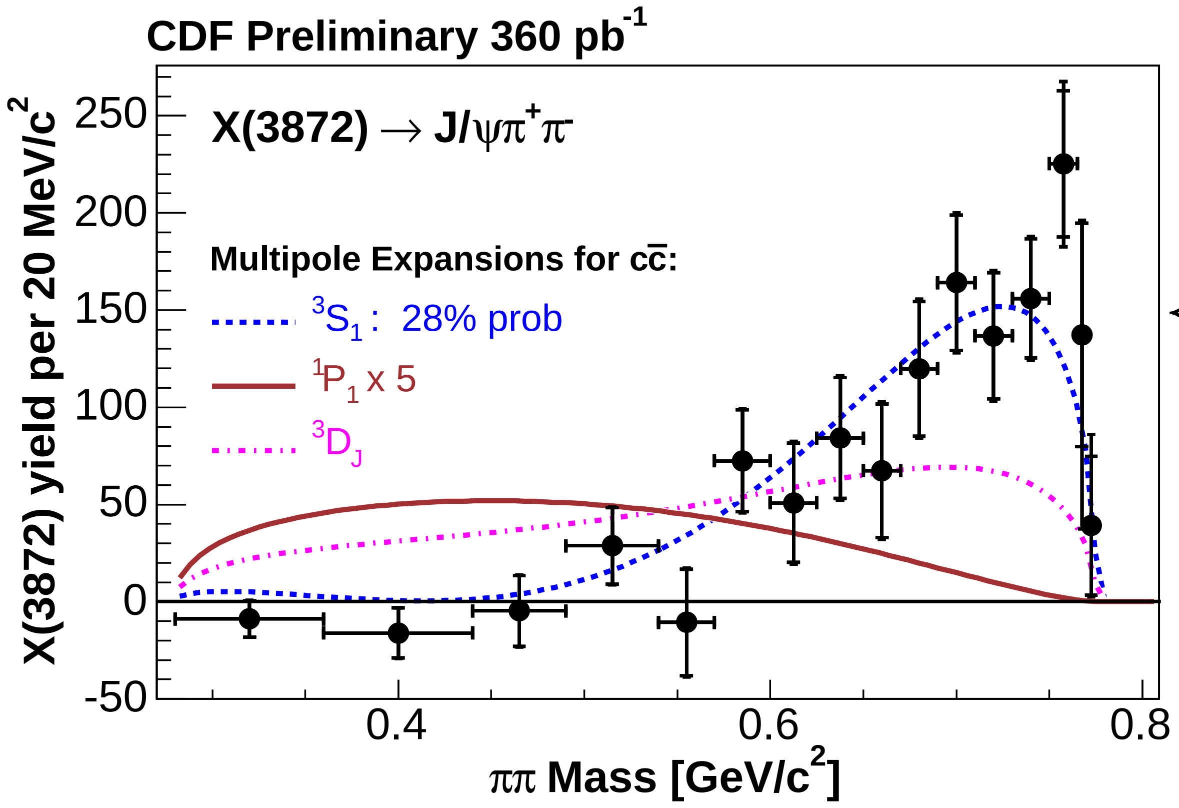
$X(3872)$ Dipion Spectrum: Charmonium Fits

- EVEN C-Parity Charmonia $\Rightarrow$ 1^{--} DiPi $\Rightarrow$ $J/\psi\rho$ Decay

i.e. $^1D_2$, $^3P_0$, $^3P_1$, $^3P_2$, $^1S_0$

- ODD C-Parity Charmonia $\Rightarrow$ 0^{++} DiPi $\Rightarrow$ Multipole Expansion

i.e. $^3D_2$, $^3D_3$, $^1P_1$, $^3S_1$ [Yan PRD22 1652 (1980)]



$\Leftarrow$ $^3S_1$ Gives Good Fit!

But There Can't Be a $^3S_1$ $c\bar{c}$ Nearby:

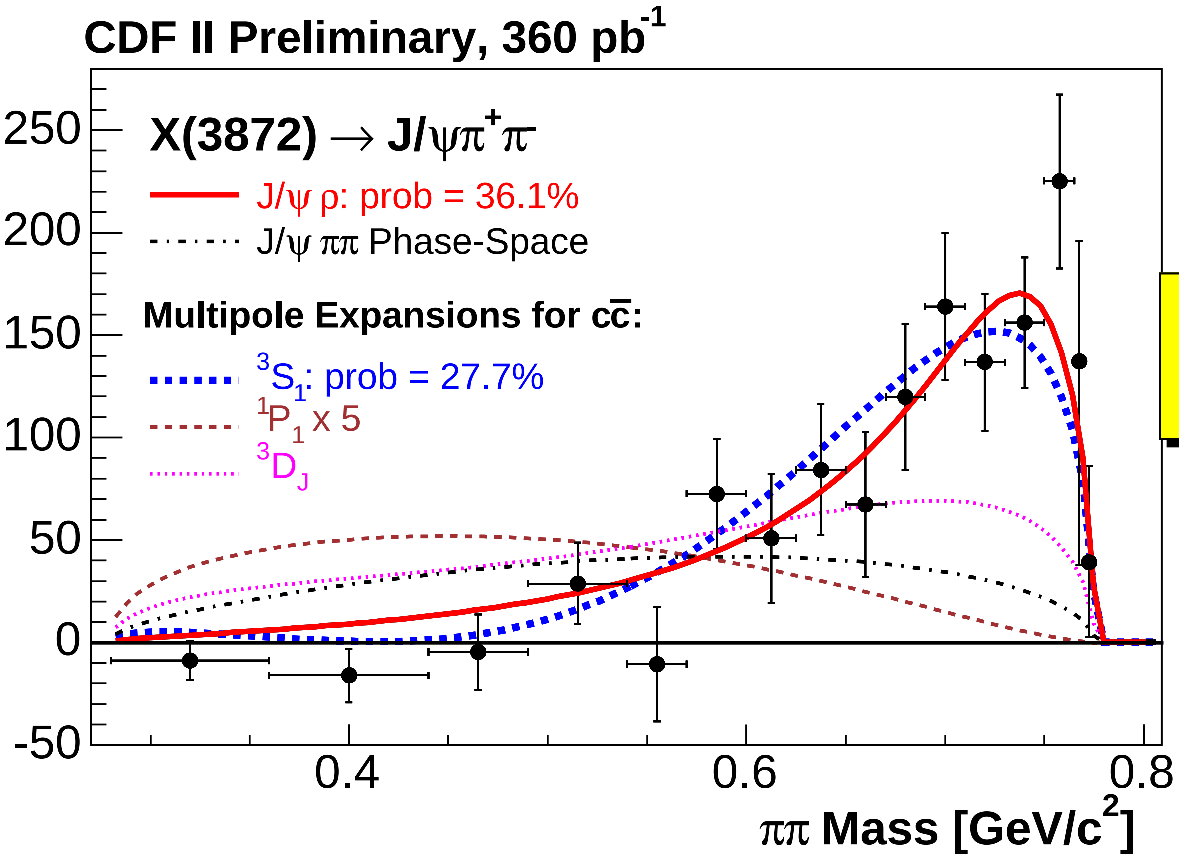
2S Is At 3686 MeV

3S Is At 4040 MeV

$\Longrightarrow$ Consider $J/\psi\rho$ Decays. . .
(*This Includes Non-$c\bar{c}$ Too*)

$X(3872)$ Dipion Spectrum: $J/\psi\rho$ Fits

- April '05 CDF Released $J/\psi\rho$ Fit Based on Simple Non-Relativistic Breit-Wigner × Phase Space:



⇐ **Excellent Agreement For $J/\psi\rho$ (Prob= 36%)**

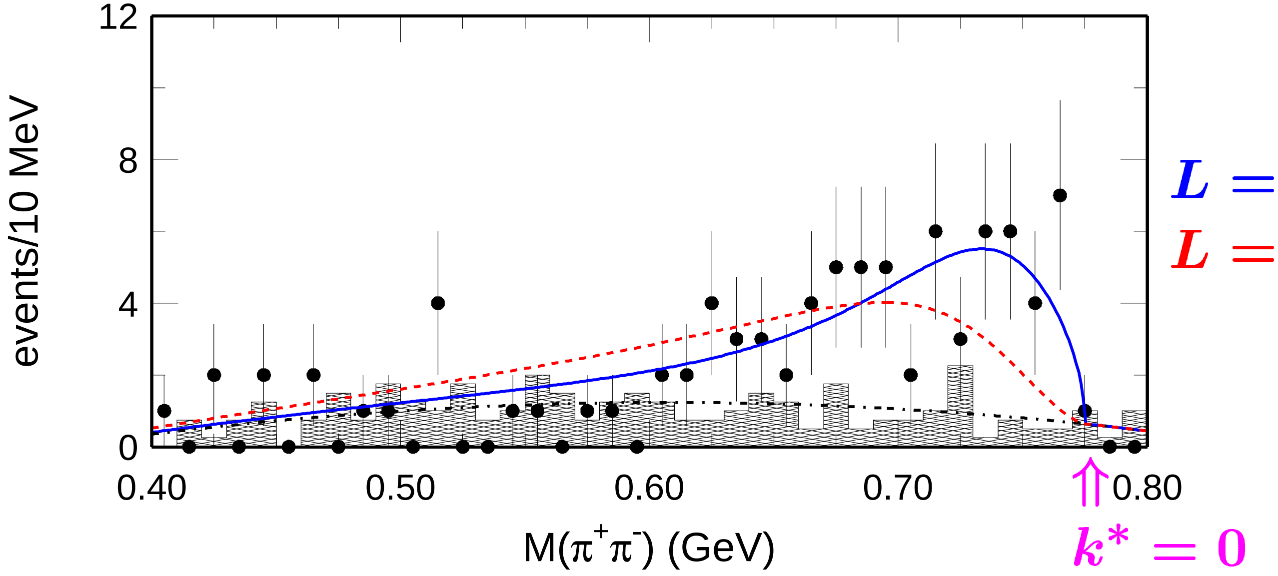
$X(3872)$ Dipion Spectrum: Belle Results

- April ‘05—Belle Issued Fit With More Sophisticated Model:

  $\Rightarrow$ Include Centrifugal Barrior for Different J/ψ-ρ Ang. Momentum (L) States:
  i.e. Phase Space Factor $k^* \rightarrow (k^*)^{2L+1}$
  [k^* *Is* J/ψ*-Momentum in Center-of-Mass*]

- Belle Fits:

[hep-ex/0505038]



$L = 0$ Fit Prob $= 28\%$
$L = 1$ Fit Prob $= 0.1\%$

$\Rightarrow$ $L = 1$ Strongly Disfavored $\Rightarrow$ X Parity Even

- Prior CDF Fit Corresponds to $L = 0$

$\Rightarrow$ Do CDF Fit With Belle’s $L = 1$ Model: CDF $\rightarrow 0.1\%$ Too*!*

- But Is This a Robust Result?. . . . . .

More Sophisticated Breit-Wigner Model

- Relativistic Breit-Wigner ←*(Rel. Not Very Important)*
- Phase Space Modified by Centrifugal Barrier
- Blatt-Weisskopf Form Factors ⇐ Absent In Belle's Model

$$\frac{dN}{dm_{\pi\pi}} \propto (k^*)^{2L_X+1} \left[\frac{f_{L_X}(k^*)}{f_{L_X}(k_0^*)}\right]^2 \frac{m_{\pi\pi}\Gamma_\rho(m_{\pi\pi})}{(m_{\pi\pi}^2 - m_\rho^2)^2 + m_\rho^2\Gamma_\rho^2(m_{\pi\pi})}$$

- Mass Dependent Width:

$$\Gamma_\rho(m_{\pi\pi}) = \Gamma_\rho^{\mathrm{PDG}} \left(\frac{q^*}{q_0^*}\right)^{2L_\rho+1} \left(\frac{f_{L_\rho}(q^*)}{f_{L_\rho}(q_0^*)}\right)^2 \frac{m_\rho}{m_{\pi\pi}}$$

- Blatt-Weisskopf (1952) Form Factors:

$$\frac{f_0(x)}{f_0(x_0)} = 1 \quad \& \quad \frac{f_{L_i=1}(x)}{f_{L_i=1}(x_0)} = \sqrt{\frac{1+R_i^2x_0^2}{1+R_i^2x^2}} \Leftarrow \begin{cases} R \rightarrow\ 0 \Rightarrow \text{No FFactor} \\ R \rightarrow \infty \Rightarrow \text{Turn-Off } L \end{cases}$$

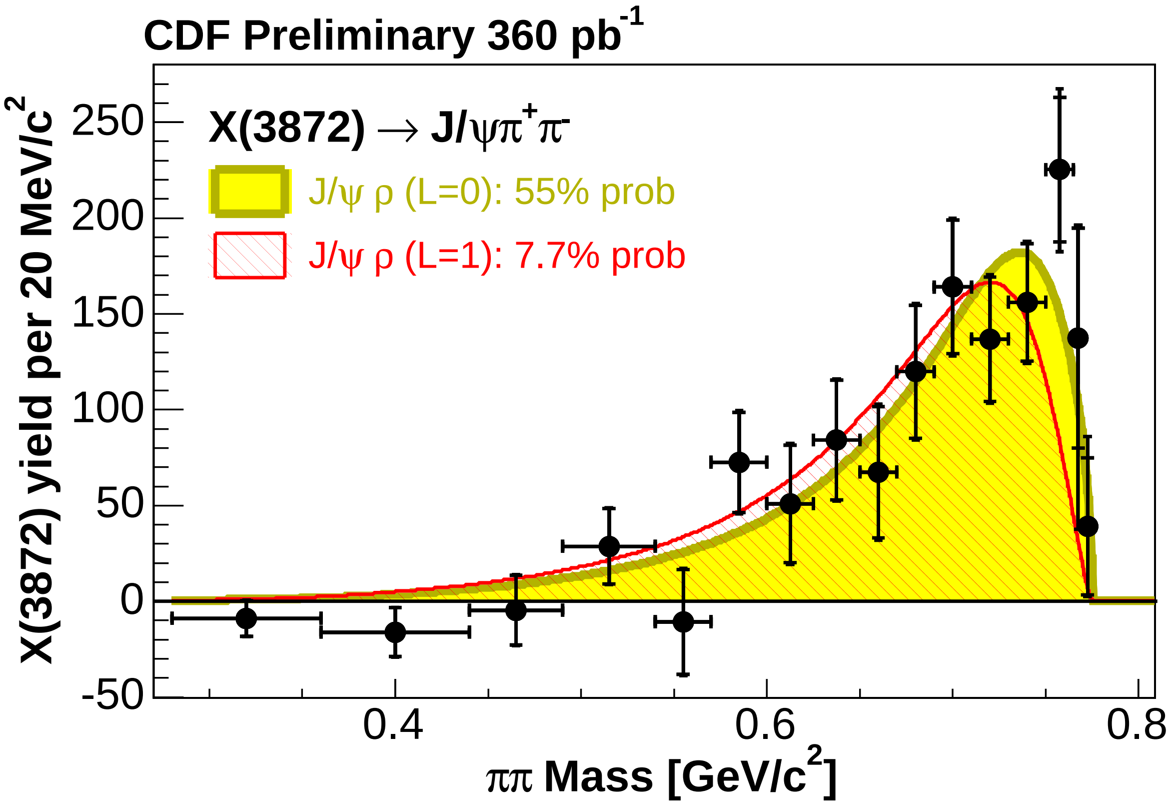
- Center-of-Mass Momenta:

$q^* = \sqrt{m_{\pi\pi}^2 - 4m_\pi^2}/2 = \pi$ Momentum in ρ Center of Mass & $q_0^* = q^*(m_\rho)$

$k^* = \sqrt{(M_X^2 - (m_\psi + m_{\pi\pi})^2)(M_X^2 - (m_\psi - m_{\pi\pi})^2)}/2M_X = p(J/\psi)$ in X CoM

$J/\psi\rho$ Fits: With Ang.-P & Blatt-Weisskopf

- Blatt-Weisskopf Radii R_i NOT Well Known
- Values Suggested From Literature: $R_X = 1.0$ & $R_\rho = 0.3$ fm
- CDF Fits:



$\Rightarrow$ $L = 0$ Is Favored. . . . . . But $L = 1$ Respectable!

- Large Modeling Uncertainties. . . **Can Not Exclude $L = 1$**

AND. . . There Are Further Shape Uncertainties. . .

$X \rightarrow J/\psi\,\omega$ Decays

- Belle: Evidence for $X \rightarrow J/\psi\,\pi^+\pi^-\pi^0$ [hep-ex/0505037]
- 3π-Mass Hugs Upper Kinematic Limit — ω Just Above Limit
  ⇒ Interpreted as $X \rightarrow J/\psi\,\omega^*$
- As Such, Belle Measures:

$$\boxed{\mathcal{R}_{3/2} \equiv \frac{\mathcal{B}(X \rightarrow J/\psi\,\omega)}{\mathcal{B}(X \rightarrow J/\psi\rho)} = 1.0 \pm 0.5}$$

- $\omega \rightarrow \pi^+\pi^-$ Negligible: $\sim 2\%$ of $\omega \rightarrow 3\pi$
- BUT — Interference Effects Need NOT Be*!*
  Crudely, Interference of Order$\sim\sqrt{\mathcal{B}(\rho\rightarrow 2\pi)\cdot\mathcal{B}(\omega\rightarrow 2\pi)}\sim 13\%$
- Suppressing Phase-Space and Blatt-Weisskopf Factors,
  Write 2π Mass Spectrum As:

$$\sim\left|A_\rho\frac{\sqrt{m\,m_\rho\Gamma_\rho(m)K_\rho}}{(m^2-m_\rho^2)+im_\rho\Gamma_\rho(m)}+e^{i\phi}A_\omega\frac{\sqrt{m\,m_\omega\Gamma_{\omega2\pi}(m)\mathcal{B}_{2\pi}K_{\omega2\pi}}}{(m^2-m_\omega^2)+im_\omega\Gamma_\omega(m)}\right|^2$$

— A_ρ & A_ω Intrinsic X-Decay Amplitudes

— ϕ Relative ρ-ω Phase

— K_i's Norm. Factors

$X \to J/\psi\,\omega$ Decays

- Describe $\omega \to 3\pi$ With Similar Breit-Wigner:
  - — No A_ρ Term
  - — SAME A_ω Amplitude
  - — $\Gamma_{\omega 2\pi}(m) \to \Gamma_{\omega 3\pi}(m)$
  - — $\Gamma_{\omega 3\pi}$ Adapted From SND Exp: $e^+e^- \to \omega^* \to \pi^+\pi^-\pi^0$

    [Achasov PRD68 052006 (2003)]

    Main Features:
    1) Use $|\vec{q}_+ \times \vec{q}_-|^2$ Matrix Element
    2) Describe as $\omega \to \rho\pi \to \pi^+\pi^-\pi^0$
- Integrate Over Mass ⇒ Relation Between 2π & 3π Yields:

$$\underbrace{(\ldots)K_\rho}_{\text{“Pure }\rho\text{”}} + \underbrace{(\ldots)\sqrt{K_\rho K_{\omega 2\pi}\mathcal{B}_{2\pi}}}_{\text{Interference}}\left|\frac{A_\omega}{A_\rho}\right| + \underbrace{(\ldots)K_{\omega 2\pi}\mathcal{B}_{2\pi}}_{\text{“Pure }\omega \to \pi\pi\text{”}}\left|\frac{A_\omega}{A_\rho}\right|^2$$

$$= \frac{1}{\mathcal{R}_{3/2}}\underbrace{(\ldots)K_{\omega 3\pi}\mathcal{B}_{3\pi}}_{\omega \to 3\pi}\left|\frac{A_\omega}{A_\rho}\right|^2$$

$(\ldots)$ = Integrals over Breit-Wigners (Phase Dependent!)

⇒ Solve for $|A_\omega/A_\rho|$...

⇒ Compute Fraction of “Pure ρ,” Interference, & “Pure ω”...

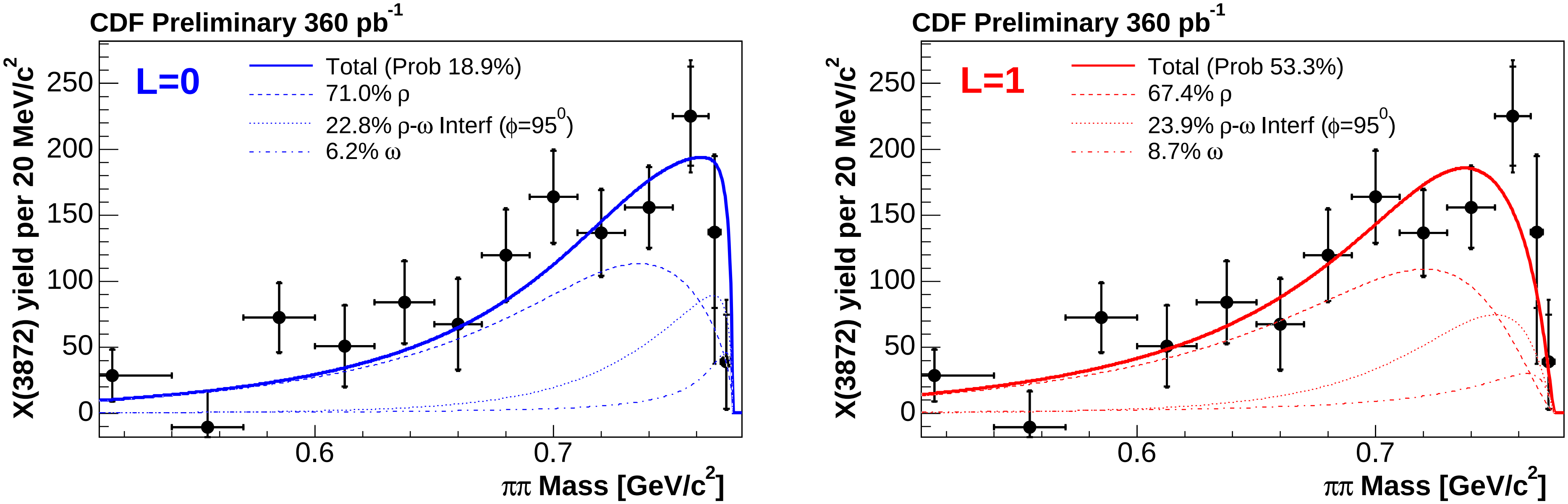
Fit Dipion Spectrum: *e.g.* 95° Phase

⊕ Assume Phase Entirely from ρ-ω Mixing $\Rightarrow \phi \sim 95^\circ$

. . . Like $e^+e^- \to \pi^+\pi^-$

⊕ Use Belle's Measurement: $\mathcal{R}_{3/2} = 1.0 \pm 0.5$

$\Longrightarrow$ Fit:

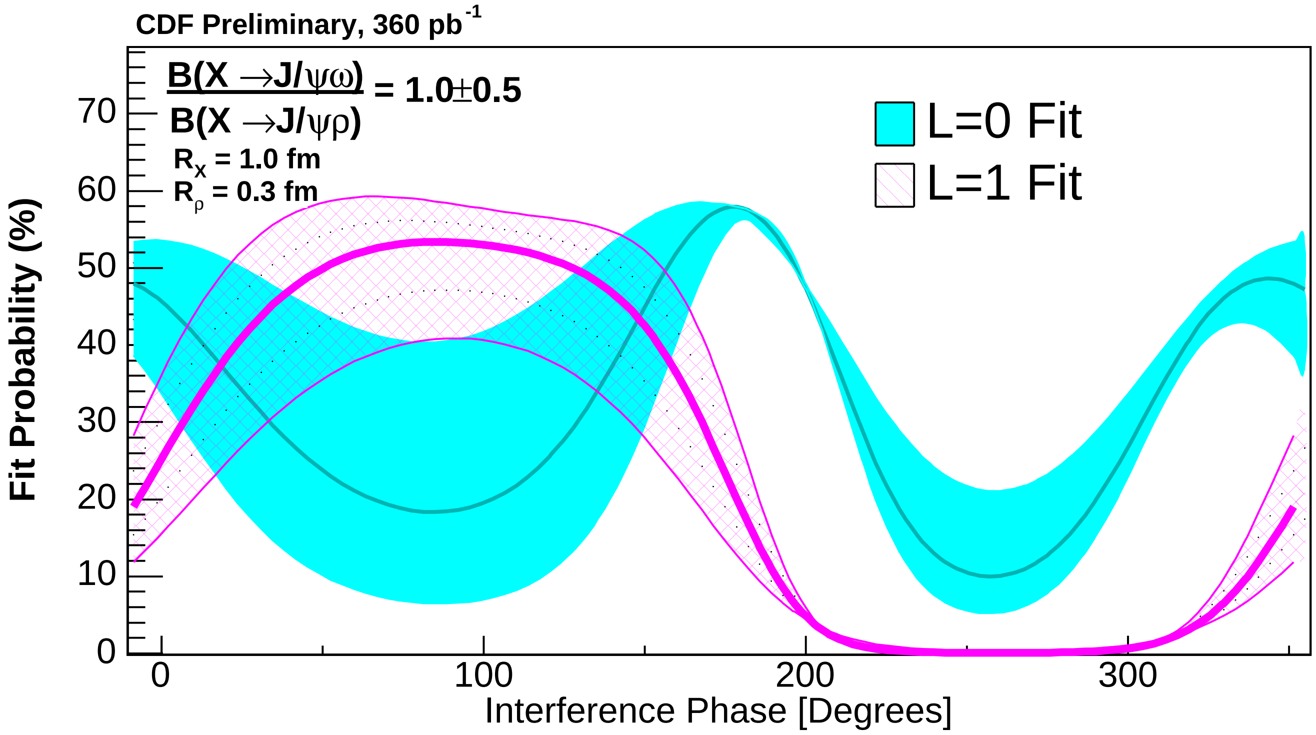


- $L = 0$ Breit-Wigner Naturally Peaks At High $M(\pi\pi)$
  - — With Interf. Starts to Peak Too Much (Prob $\downarrow 19\%$)
- $L = 1$ Briet-Wigner Peaks Not So High in $M(\pi\pi)$
  - — Interf. Makes-Up Shortfall (Prob $\uparrow 53\%$)

$\Rightarrow$ Models Can Accommodate BOTH $L = 0$ & 1 $\Leftarrow$

CDF Fit Probability Vs. Phase:

- Use Computed Fractions ⇒ Fit Prob. as Function of ϕ:



- Large Prob. for $L = 0$ No Matter What the Phase
- For Certain Phases $L = 1$ Fits Have Very High Prob.
- $L = 0$ Prefers Small $\mathcal{R}_{3/2}$ — $L = 1$ Prefers Large $\mathcal{R}_{3/2}$
- Big Picture Insensitive Over Belle's $\pm 1\sigma$ Error on $\mathcal{R}_{3/2}$

— But Sensitive to R_X & Shapes of $\Gamma_{\omega 2\pi}(m)$ Vs. $\Gamma_{\omega 3\pi}(m)$

$X(3872)$ Summary:

- X-Production At Tevatron Looks Charmonium-Like

⇒ Charmonium? — OR At Least Large $c\bar{c}$ Component?

⇒ If D-$\overline{D}^*$ Molecule: Little Penalty to Produce Fragile Object!

- $\pi\pi$-Mass Spectrum:

⇒ Multipole Expansion $\Longrightarrow$ No Viable $C_X = -1$ Charmonia

⇒ $X \to J/\psi\rho$ Fits Very Well! $\Longrightarrow C_X = +1$ ⇐*Belle Now Sees* $J/\psi\gamma$*!*

⇒ Model Uncertainties Allow BOTH S- & P-Wave Decays

e.g. Odd Parity States Like $^1D_2$ (2^{-+}) *of* $c\bar{c}$

⇒ Intrinsic Rate of X Decay to $J/\psi\rho$ IS Suppressed (Isospin?):

$\mathcal{B}(J/\psi\rho) \approx \mathcal{B}(J/\psi\omega)$ YET ρ Phase-Space $\gg$ ω Phase-Space

- First Consideration of ρ-ω Interference for $X(3872)$

⇒ P-Wave Fits Improved by ρ-ω Interference

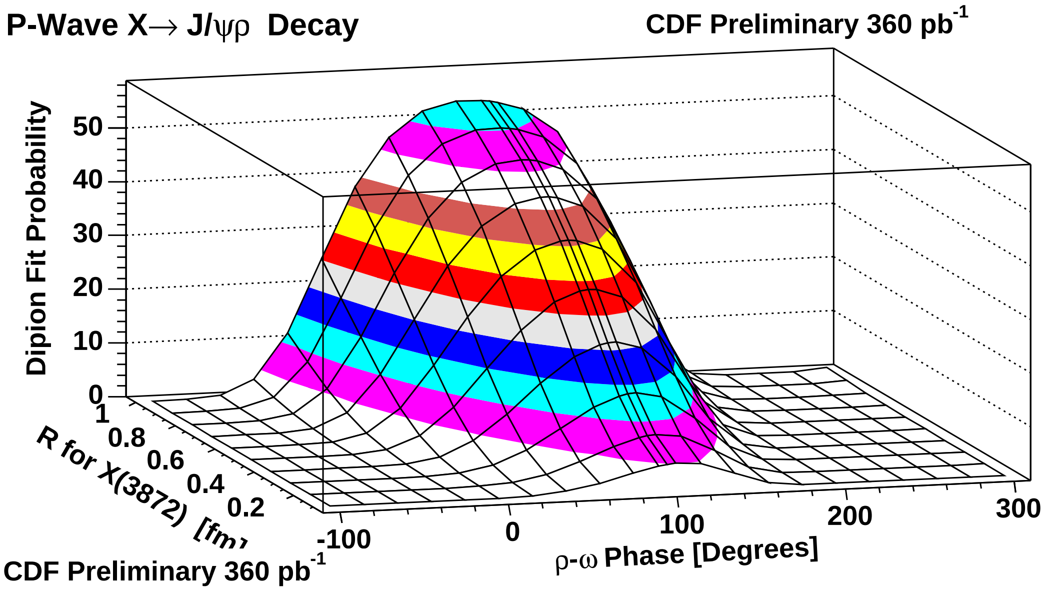
⇒ Belle's $J/\psi\,\omega$ Signal Nicely Accommodated within CDF Fits

BACKUP SLIDES

ρ-Model Sensitivity:

- Key Ingredient in Breit-Wigner Is Blatt-Weisskopf Radius R_i
- Commonly Used, But Not Well Constrained by Other Exp's
- $L = 1$ Fit Prob
  Versus R_X and Phase:

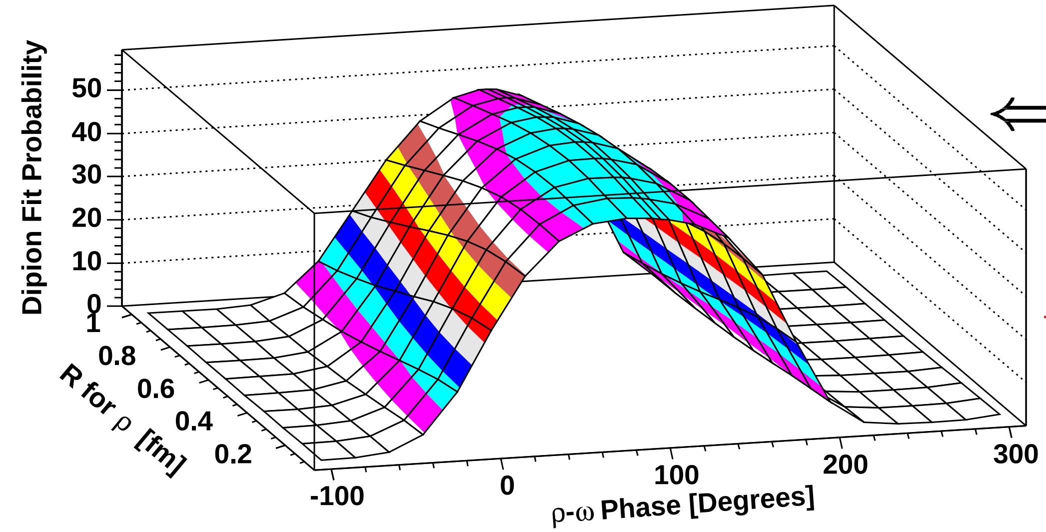
Large R_X Preferred $\Rightarrow$



$\Uparrow$

$\Leftarrow$ 5% Prob Contours

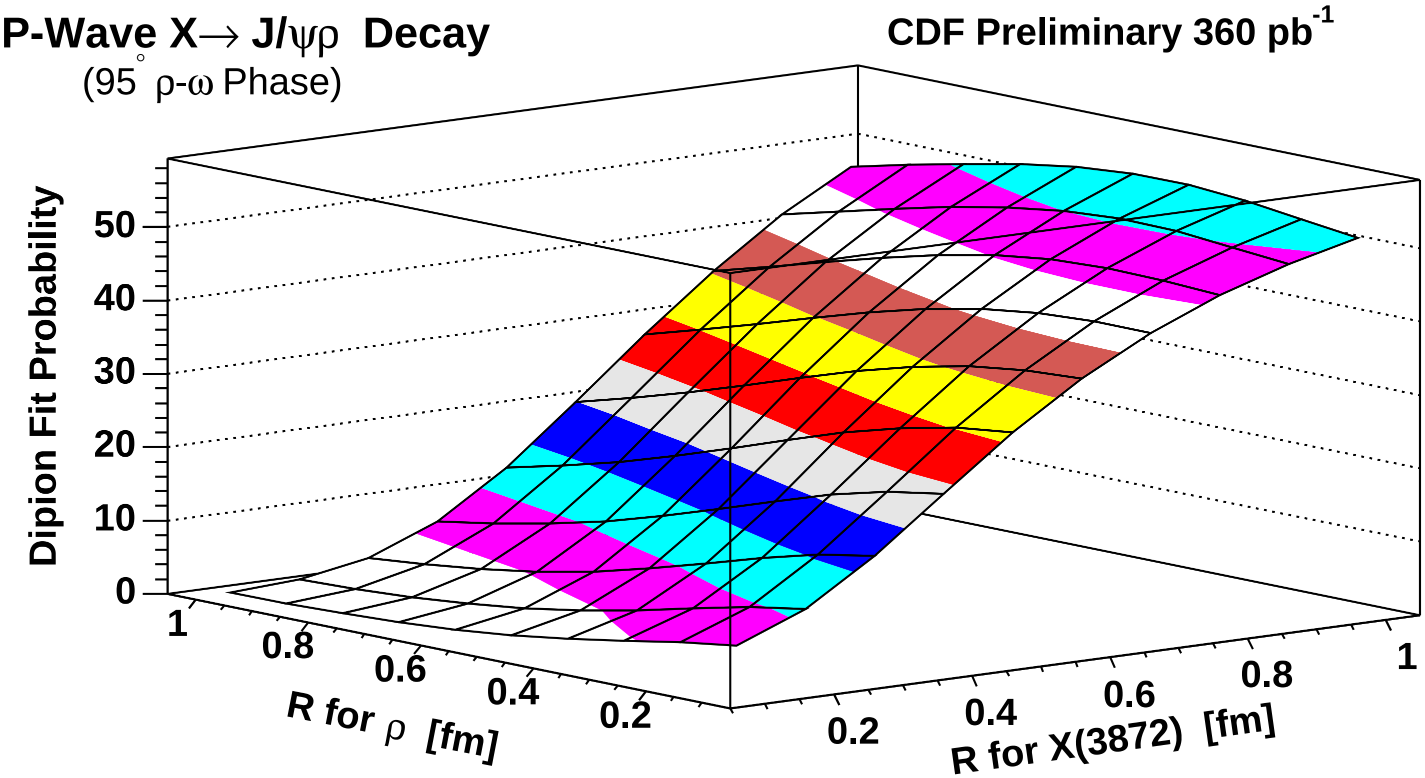
- Weak Effect for R_ρ:



$\Leftarrow$ Small R_ρ Preferred

Model Sensitivity: Blatt-Weiss. R_ρ & R_X

- For $\phi = 95°$
- $L = 1$

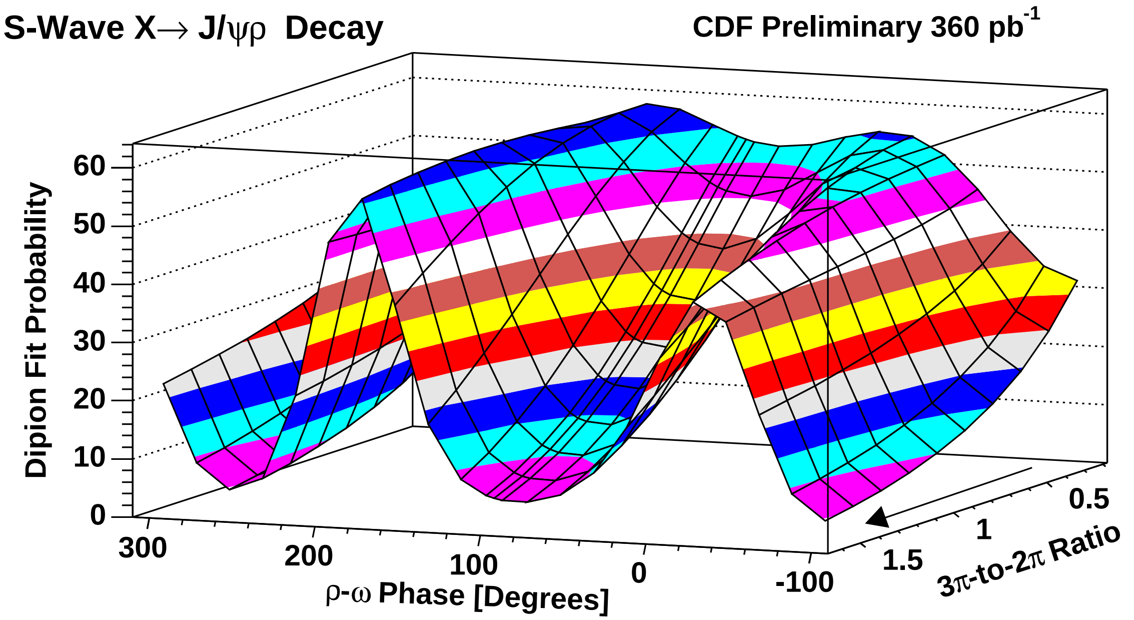


- Strong R_X Dependence
- Weak R_ρ Dependence

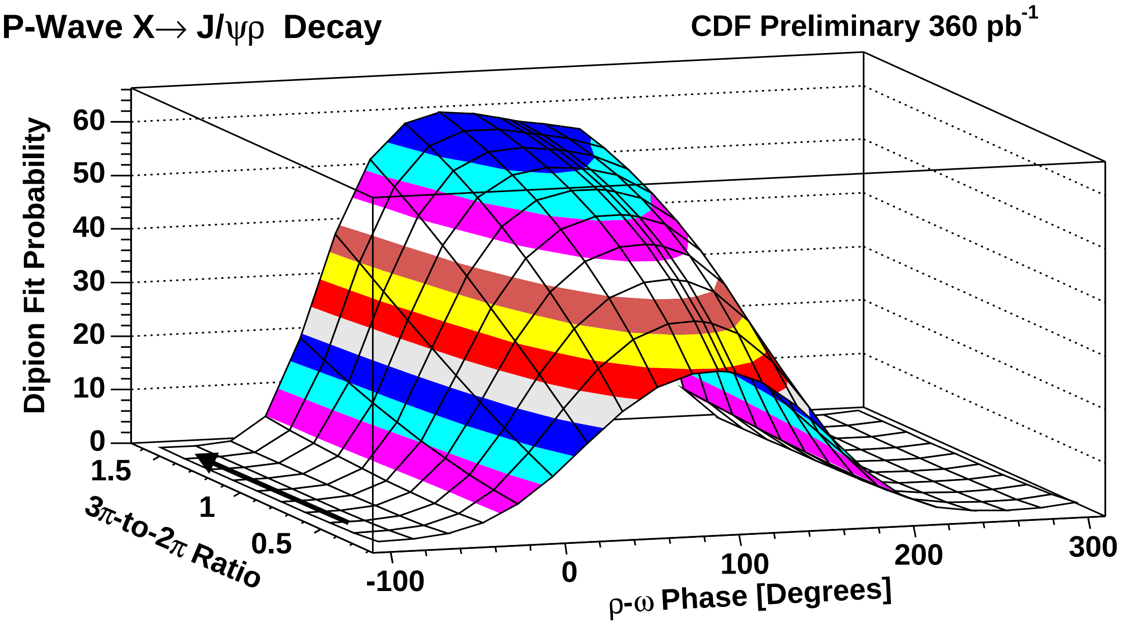
$\Longrightarrow$ But Big Picture Unchanged Over Broad Range of R's

ρ-Model Sensitivity: ω/ρ-Ratio & Phase

- $L = 0$

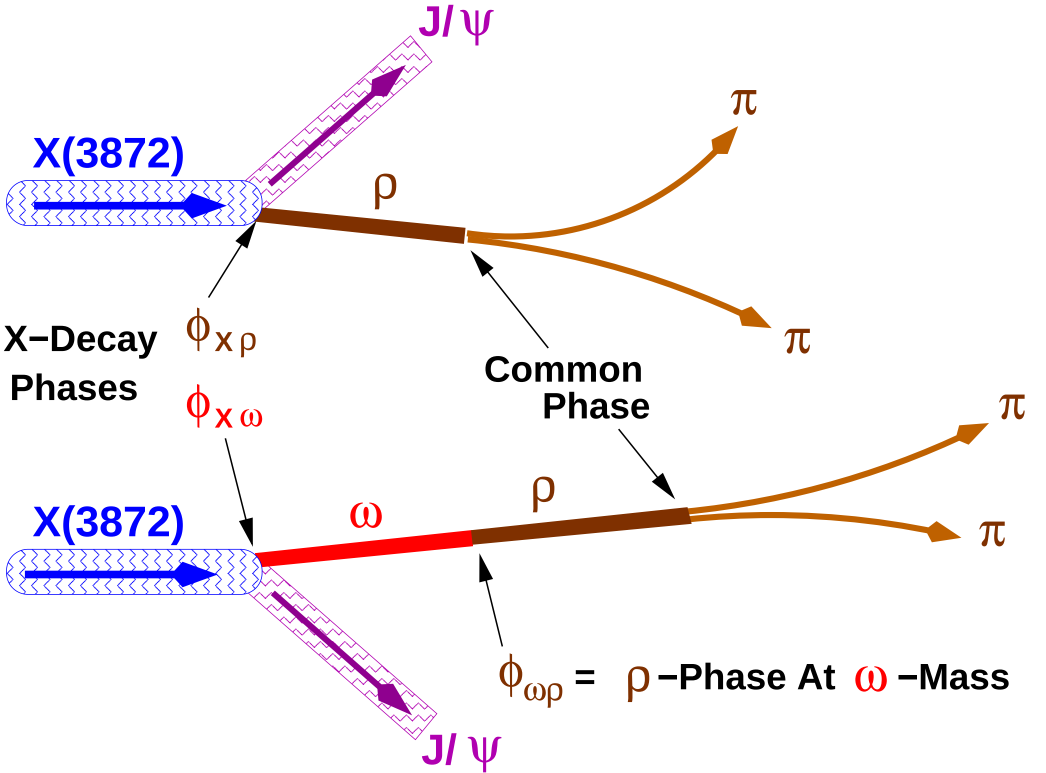


- $L = 1$



Interference Phase: 95°

- Total Phase $\phi_{Total} = \boxed{\text{Phase at } X \text{ Decay}} + \boxed{\rho\text{-}\omega \text{ Phase}}$
- If $\phi_{X\rho} = \phi_{X\omega} \Rightarrow \phi_{Total} = \phi_{\rho\omega}$



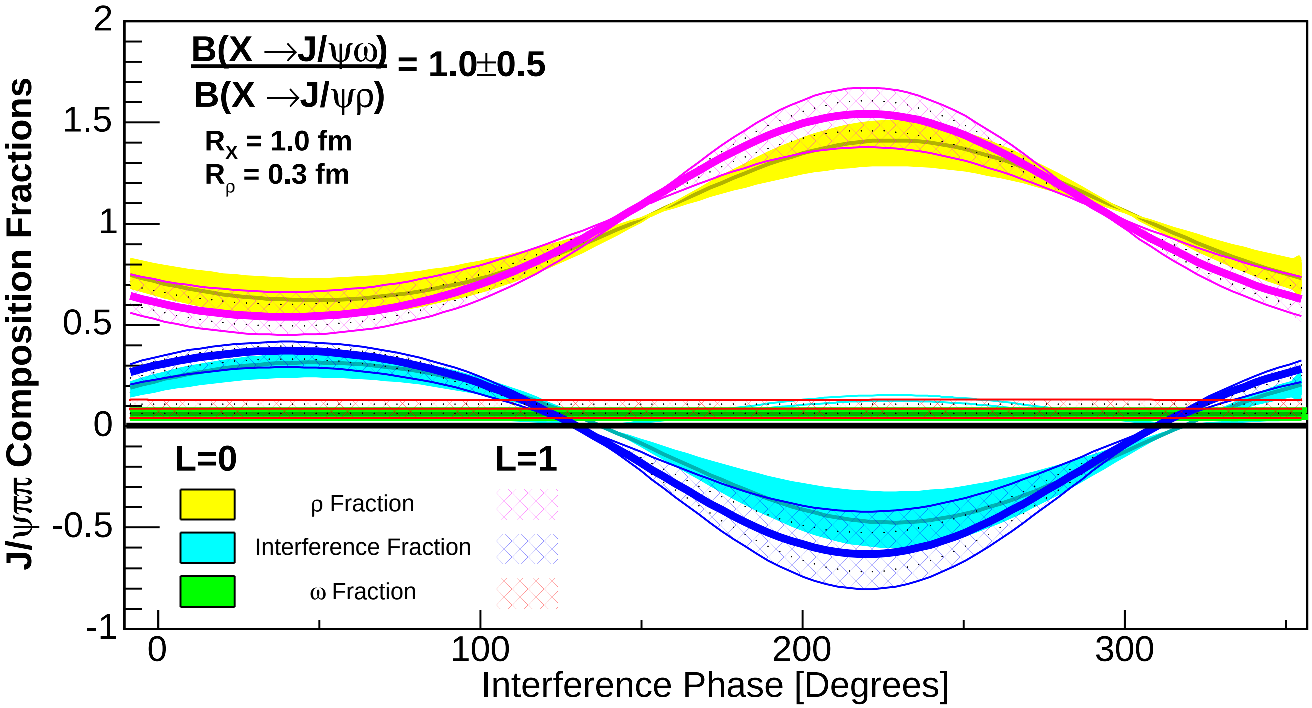
⇐ In Mixing Model Where $\omega \to 2\pi$ Is Via Virtual ρ

$$\rho\text{−Prop.} \sim \frac{1}{(m_\rho - m_\omega) + i\Gamma_\rho/2} \longrightarrow \phi_{\omega\rho} \sim 95^\circ$$

$\Rightarrow$ Phase $\sim 95^\circ$ [Similar to Phase in $e^+e^- \to \pi^+\pi^-$ Data]

Fractions Versus Phase:

- Compute Fractions as Function of ϕ
- Bands Span Belle's $\pm 1\sigma$ Range



⇐ Pure ρ

⇐ Interf

⇐ Pure ω

- Not *Much* Different for $L = 0$ & 1
- Fractions Are Mathematical Computation of the Model

  — Nothing to Do With CDF Data*!*
- Data Says How Well These Fractions Work $\Longrightarrow$ CDF Fits

Dipion Mass Spectrum:

- Correct for Efficiencies ⇒

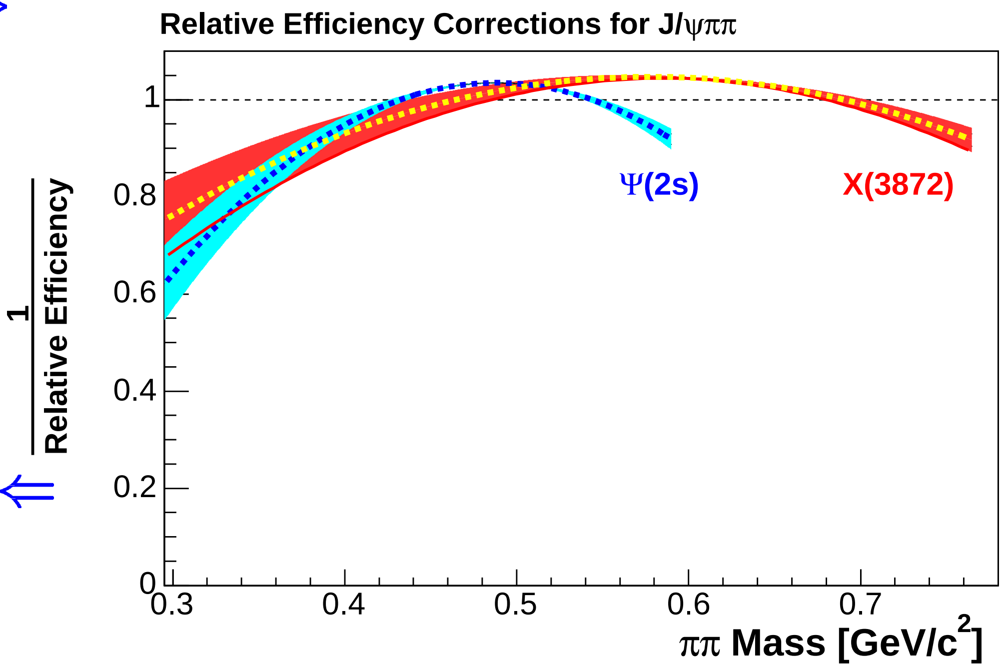
  (*Small Effects*)

  $p_T(J/\psi\pi\pi) > 6$ GeV

  $|\eta(J/\psi\pi\pi)| < 0.6$

  $\Delta R < 0.7$

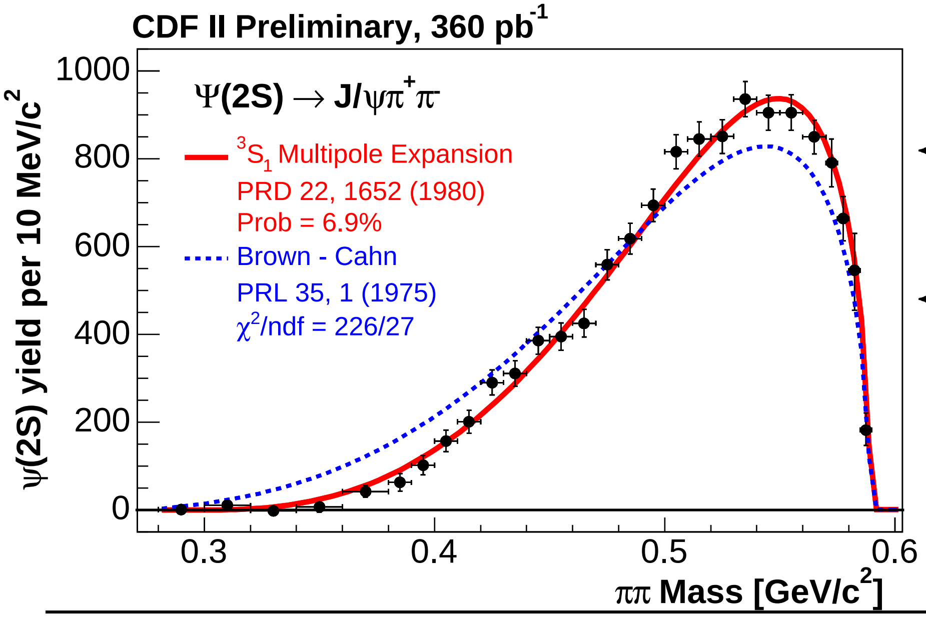
  Fit Quality Cuts...



- Obtain Dipion Spectrum ⇐

  — $\psi(2S)$ Is Good

  Reference Signal:



⇐ Good Agreement With QCD Multipole Expansion

⇐ Also With Higher Stat. BES

[BES PRD62 032002 (2000)]

Prompt *vs* B-Production:

Standard Technique to Distinguish B From Non-B Production:

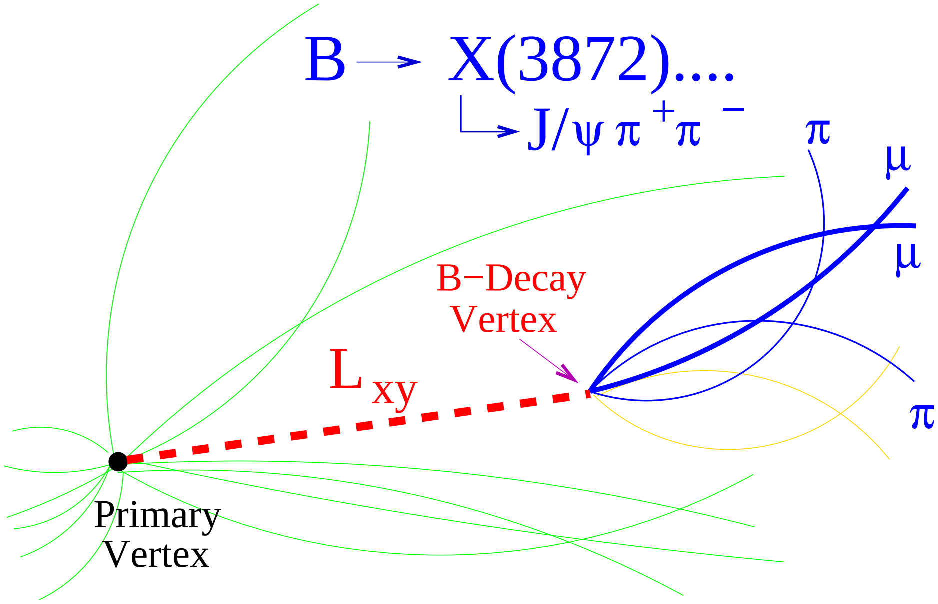
- Measure Apparent "Lifetime" of $X(3872)$ $[\tau(X) = 0\,!]$
- Fit Relative "Prompt" and "Displaced" **Fractions**

Details:

- Measure Displacement of Vertex: L_{xy}
- "Proper Time":

$$ct \equiv \frac{M(J/\psi\pi^+\pi^-)}{p_T(J/\psi\pi^+\pi^-)} L_{xy}$$

- Missing B-Decay Products
  $\Longrightarrow$ NOT True ct
  $\Longrightarrow$ Don't Care!
- Likelihood Fit:
  $\rightarrow$ **Fraction of Displaced X's**



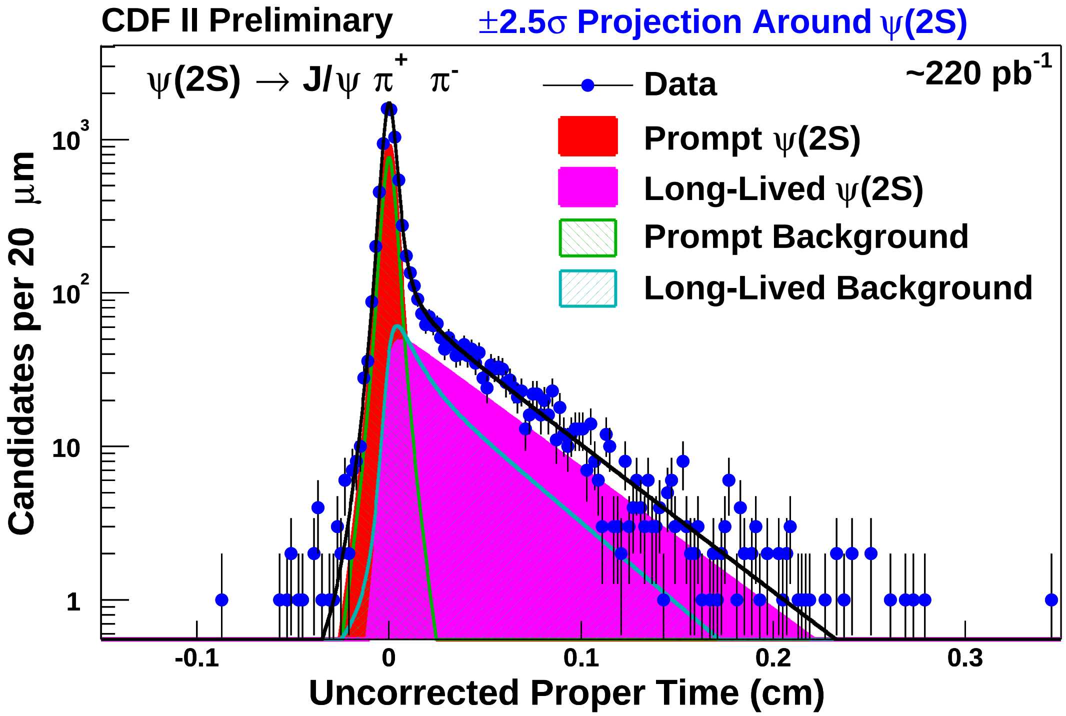
$\Longrightarrow$ Use Same X Sample as M-Measurement: 220 pb^{-1}

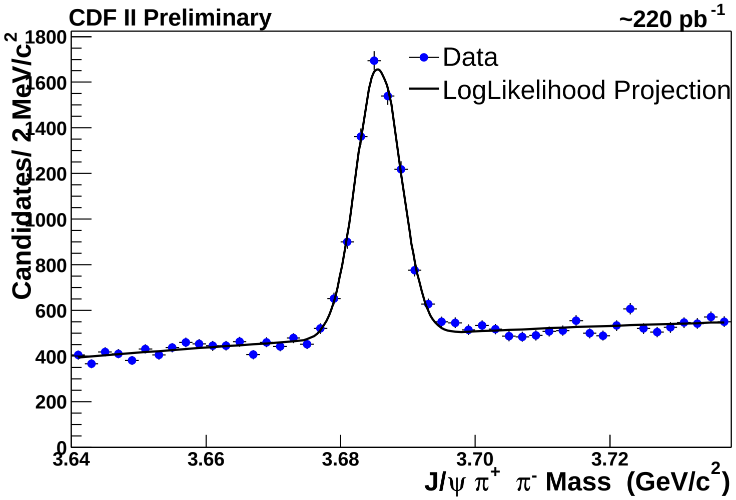
$\Longrightarrow$ +Vertexing Cuts (SVX, $\sigma(Vrtx)$,. . .): -15%

. . . . & $\psi(2S)$ *a Good Reference Signal. . .*

Displaced Fraction: $\psi(2S)$

Simultaneous M & ct Likelihood Fit: Mass Projection:





⇐Proper-Time Model:

Prompt:
Res. Smeared Gaussian

Long-Lived:
Res. Smeared Exp.

Resolution: 2 Gaussians

Displaced $\psi(2S)$-Frac:

$$\boxed{28.3 \pm 1.0 \pm 0.7\%}$$

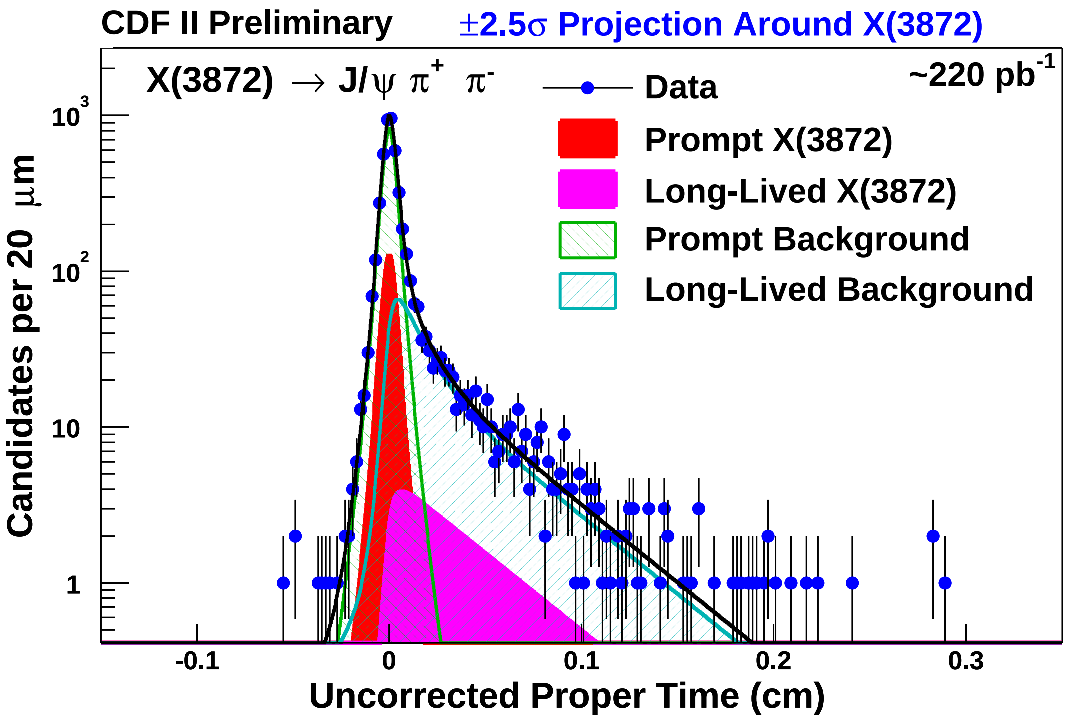
$\Rightarrow \psi(2S)$ Mostly PROMPT

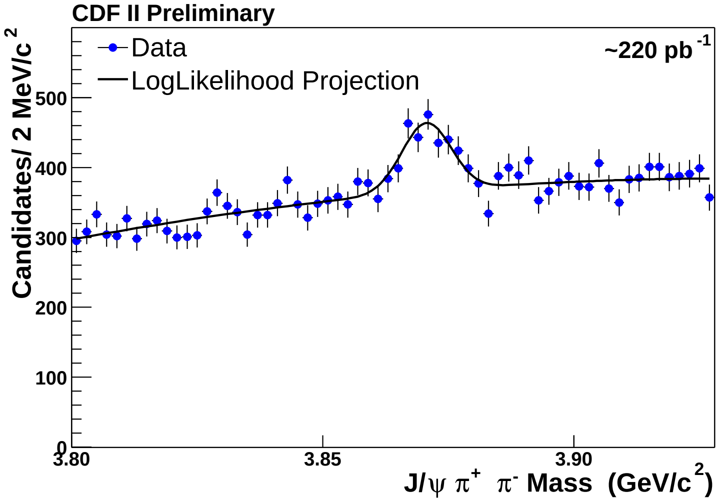
[Previously Studied: CDF PRL**79**, 572 (1997)]

Displaced Fraction: $X(3872)$

Same Procedure for $X(3872)$. . . . . . Use $M(\pi\pi) > 500\,\mathrm{MeV}/c^2$. . .

Mass Projection:





Displaced X-Frac:

$$\boxed{16.1 \pm 4.9\,(stat)\ \pm 2.0\,(syst)\%}$$

$\Rightarrow X$ **Mostly** **PROMPT!**

$B \to X(3872)\ldots$ Significance:

- Belle: KNOW $B \to X\ldots$ is Significant
- Now KNOW **Prompt Dominates CDF Signal**. . .

  But Error on B-Fraction Not Small. . . $\mathbf{16.1 \pm 4.9}(stat)\%$

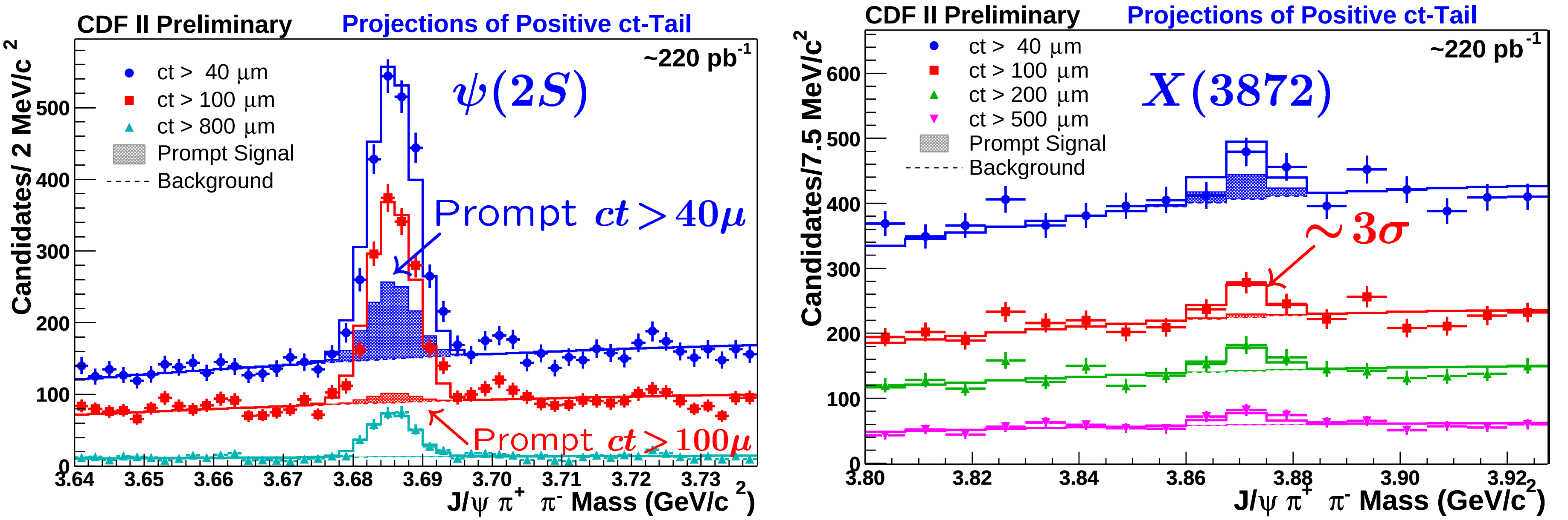
  $\Longrightarrow$ Could It "**ALL**" Be Prompt?

$>$ Naively: $16.1/4.9 \to$ $\sim\mathbf{3.3}\sigma$ Null Hypothesis Excluded

$>$ MC: NO B-Signal to Fluctuate $\geq 16.1\%$ is 3σ

$>$ Still. . . Good to Take Direct Look at Data. . .

$\Longrightarrow$ Project Likelihood for High-ct Tails:



$\Longrightarrow$ Likelihood Describes Tails Well

$\Longrightarrow$ Even Visually: $\sim 3\sigma$ B-Component for X!